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An Automated Maintainability Prediction Tool Integrated with Computer Aided Design

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Abstract

Design for maintainability is an important aspect of aircraft design, with maintenance representing 10 – 25% of the direct operating cost of an aircraft [1]. Design for Maintainability incorporates many aspects including assembly/ disassembly time, accessibility, visibility and ergonomics and it can be challenging for design engineers to consider at the design stage due to the time taken and specialist knowledge required.

There are a number of existing tools that can be used to assess individual aspects of maintainability but these were mostly developed as paper based tools that require the designer to visualise the maintenance task while studying the engineering drawings or observing an operator performing the task. This paper presents an automated maintainability prediction tool that is integrated with the CATIA v5 Computer Aided Design software. The tool allows the designer to rapidly estimate the maintenance corrective time for a maintenance task utilising a CATIA product model as its input. It uses elemental maintenance action standard times from MIL-HDBK-472 Procedure V to estimate maintenance task times, and RULA, OWAS and LBA ergonomics methods to apply a time penalty based on the operator ergonomics during the task.

In this paper the maintainability prediction tool will be tested on a range of simple aircraft maintenance tasks to assess how accurately it can predict maintenance corrective times. The results from the tool are compared to experimental data from physical trials for each maintenance task and the results discussed.

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Keywords: Aircraft Design; Maintainability Prediction; Computer Aided Design; Ergonomics; MIL-HDBK-472

1. Introduction

Design for Maintainability is an important part of the product development process that has attracted more attention in recent decades. In the aerospace industry, it is estimated that maintenance represents 10 – 25% of the direct operating cost of an aircraft [1] and due to the highly competitive global market, great effort is given to consider maintainability as early as possible in the development stage of an aircraft. A product in which maintainability aspects have been taken into consideration would produce multiple benefits and great cost savings in the overall lifecycle of the product.

Maintainability is defined by MIL-STD-721 [8], as “the measure of the ability of an item to be retained in or restored to specific conditions when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources at each prescribed level of maintenance and repair.”

One of the challenges of improving maintainability is to accurately predict maintenance times early in the design process. Design engineers are required to consider many different down-stream aspects during the design process and they need simple tools that can rapidly allow them to compare different design alternatives. An interesting approach that satisfies the overall goals of improved maintainability is the development of a software tool that is integrated with the existing design toolset to allow designers to predict maintenance times early in the design process. With that in mind, the use of 3D design software CATIA in connection with Visual Basic for Applications (VBA) is proposed in order develop an application for automated maintenance task time

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prediction. Inputs from a CATIA product model combined with elemental maintenance action standard times from MIL-HDBK-472 will provide an initial time estimate. The use of ergonomics methods, Rapid Upper Limb Assessment (RULA), Ovako Working posture Assessment (OWAS) and the Lower Back Analysis (LBA) combined using the Posture Evaluation Index (PEI) will be used to calculate a time penalty index to incorporate the working posture into the time estimate. To evaluate the accuracy and efficiency of the developed tool, a series of physical experiments have been conducted regarding simple maintenance tasks on an aircraft.

2. Literature Review

2.1 Maintainability Prediction Methods

The most notable literature regarding maintainability prediction is MIL-HDBK-472, which was first published in 1966 containing four approaches. A revision was published in 1984 with the Procedure V being the most recent and therefore the most accurate maintainability prediction method [4] and later incorporated into MIL-HDBK-470A [2]. All of the procedures depend upon reliability and maintainability data and experience [4] and are based on two key parameters: failure rate and repair time.

In MIL-HDBK-472 Procedure V, two methods can be used in order to predict maintainability. Method A is to be applied early in the design phase and method B, in which a detailed design is needed, is used more often at a later stage in the design process. Overall, method B is more easily implemented in a design tool because elemental activities are combined for time estimation, which could then be simulated in a virtual environment. All the elemental activities should be established at the beginning of the process either by experiment or using the provided time standards. Then the elemental activities are summed to provide the total time.

In this research only the tabulated elemental maintenance action times from MIL-HDBK-472 Procedure V are used and not the full maintainability prediction method. Tabulated data is provided for common maintenance tasks including removal and replacement of fasteners, electrical components and other common components. The simplicity and ease of access to tabulated data makes procedure V the most convenient one to integrate in a CAD system, like CATIA, however accessibility and visibility aspects are not covered by this method. Also, whilst the elemental maintenance times used in MIL-HDBK-472 Procedure V are more recent than other maintainability prediction methods, the underlying data is still quite dated as they were published in 1984.

2.2 Accessibility and Ergonomics

Accessibility is defined as a design feature that affects the ease of access to an area for the performance of visual and manipulative maintenance [8]. According to the DOD-HDBK-791 [8], accessibility does not simply mean that the items could be reached. If the items can only be reached by special tools or in an awkward body position, the accessibility score should be lower.

Ergonomics is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and it applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance [9]. Various methodologies have been developed through the years in order to evaluate and predict ergonomic aspects. RULA (Rapid Upper Lib Assessment) is a postural targeting method for estimating the risks of work-related upper limb disorders [5]. A RULA assessment gives a quick and systematic assessment of the postural risks to a worker. It makes use of qualitative scores and the analysis can be conducted before and after an intervention to demonstrate that the intervention has reduced the risk of injury. The RULA action levels define the level of urgency to change how a person is working as a function of the degree of injury risk. In Table 1, the classification of RULA score can be seen, along with an interpretation

Table 1: RULA action levels [5]

Action level	RULA score	Interpretation
1	1-2	The person is working in the best posture with no risk of injury from their work posture.
2	3-4	The person is working in a posture that could present some risk of injury from their work posture, and this score most likely is the result of one part of the body being in a deviated and awkward position, so this should be investigated and corrected.
3	5-6	The person is working in a poor posture with a risk of injury from their work posture, and the reasons for this need to be investigated and changed in the near future to prevent an injury.
4	7+	The person is working in the worst posture with an immediate risk of injury from their work posture, and the reasons for this need to be investigated and changed immediately to prevent an injury.

RULA, as a method, evaluates and focuses only on the upper body and, as a result, the lower body is not taken into account. Therefore, another methodology was developed, called Rapid Entire Body Assessment (REBA), which, extends the RULA method to evaluates the whole body postural musculoskeletal disorder (MSD) risk [10]. RULA has been used in this research in order to link to the available functions in CATIA.

The National Institute for Occupational Safety and Health (NIOSH) published a lifting equation for the assessment of low-back disorder risk in jobs with repeated lifting [11]. Based on the NIOSH method the lower back analysis (LBA) score was defined as the compression on the L4 and L5 lumbar discs expressed in Newtons (Calder and Potvin [7]). In 1977, Karhu, Kansi and Kuorinka [11] created a concept for the analysis of the working postures named Ovako Working posture Assessment System (OWAS) in which the working postures are classified into four categories by body member. These are: back (four postures), arms (three postures), legs (seven postures) and the weight of the handled load (three types). A drawback of this method is that it does not provide any information regarding the elbows and the wrists.

Di Gironimo et al. [12] proposed an ergonomic analysis based on the critical posture in a task called the Posture Evaluation Index (PEI). The PEI integrates the results of LBA, OWAS and RULA to evaluate the comfort level of the posture. Di Gironimo et al. presented their first research to determine the better car maintenance position according to the PEI score in 2004. The PEI is calculated using equation 1[12]:

$$PEI = \frac{LBA}{3400} + \frac{OWAS}{4} + \frac{RULA}{7} \quad (1)$$

Where PEI is calculated as the weighted sum of the three ergonomic scores LBA, OWAS and RULA. LBA is normalized with the NIOSH limit for the compression strength (3400N), which could be regarded as the maximum load on the back and RULA and OWAS are normalized with their maximum values of 7 and 4 respectively. The amplification factor (m_r) is applied to the RULA factor because it is believed that the upper limbs are subject to the highest level of fatigue and have a higher risk of muscular-skeletal disease. A value of 1.42 is used for the amplification factor based on the results of Columbini et al. [13]. Di Gironimo states that PEI score should be in the range 0.47 (no loads applied to the hands, values of joints angles within the acceptability range) to 3.42 (compression strength on L4/L5 lumbar disks equal to the NIOSH limit 3400N; values of joints angles not acceptable).

3. Methodology

The aim of this research is to develop a software tool to predict maintenance time within the CATIA CAD software environment. The methodology is applicable both during the design stage (to remind the designers to keep the maintainability in mind and improve it in the aspect of accessibility and visibility), and in the maintenance environment where it could allow managers to consider different maintenance task sequences to minimize maintenance time. From these two points, the methodology could benefit both the designers and managers.

The maintainability assessment software tool comprises four basic elements:

1. A database of maintenance task times for elemental maintenance tasks from MIL-HDBK-472 Proc. V.
2. A penalty factor for task ergonomics based on the Postural Evaluation Index [12].
3. Integration with the CATIA software using the VBA programming interface to obtain product details and ergonomic assessment scores.
4. A user interface.

The database from MIL-HDBK 472 Procedure V has been transferred to a Microsoft Excel spreadsheet, containing all the necessary elemental task time information. MIL-HDBK-472 Procedure V does not take into account the postural difficulty [4] so the PEI method has been used to calculate a time penalty for postural difficulty from the calculated Procedure V time estimate using equation 1. The LBA and RULA can be measured using functions in CATIA, however, CATIA does not possess a function to obtain the OWAS value, which has to been calculated by the user. Fortunately, compared with the other two parameters, the way to calculate the OWAS value is much simpler and can be input by the user using drop down menus in the software tool.

The PEI score is converted into a time penalty applied to the maintenance task time. Zhao [14] performed a series of experiments repeating the same elemental maintenance tasks in different postures to determine the time penalty associated with different postures and PEI scores. He defined a third order polynomial equation based on the experimental results to calculate the time penalty c (Equation 2) [14].

$$c = \frac{0.0514PEI^3 + 1.9123xPEI^2 - 2.051PEI + 35.33}{34.79} \quad (2)$$

The time penalty c is applied to the elemental task times from MIL-HDBK-472 to take into account postural difficulty using equation 3.

$$T_e = c * T_s \quad (3)$$

Where T_e is the final estimated time, c the co-efficient of the time penalty and T_s is the standard calculated time from MIL-HDBK-472. For the maximum PEI score of 3.42 the penalty factor c is 1.52.

The integration with CATIA allows product design information, including fastener types and part weight, to be read directly from the CATIA product model. The user interface for the software tool can be seen in Fig. 1. The maintenance tasks are listed in the top left corner, the CATIA product in the bottom left corner, the postural analysis in the top right and the results in the bottom right. The results can be displayed on the screen or exported. The software tool provides a time estimate for each maintenance activity, with a penalty for the operator's posture. A standard deviation for each task is also calculated. A final maintenance task time for the whole task and combined standard deviation are provided.

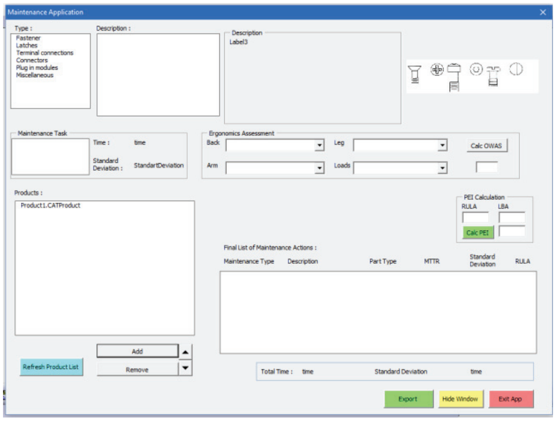

Fig. 1. User interface for Maintainability Predication Tool

4. Experimental Study

The maintainability prediction tool has been tested on a range of simple maintenance tasks undertaken on an aircraft flight deck. The aircraft used for testing was the forward fuselage of a scrapped Nimrod MRA4 aircraft owned by Cranfield University. The maintenance tasks were selected as representative remove and replace tasks for items that are accessible from the flight deck and cabin. Four tasks have been undertaken: two access panel covers, one set of avionics boxes and one avionics rack cover [15].

4.1 Task 1: Remove and Replace Upper Cover

Maintenance activities to be performed for the upper cover:
Task 1.1: Unfasten eight Tridair fasteners
Task 1.2: Remove the cover and place it on the floor
Task 1.3: Pick up the cover again and position it in place
Task 1.4: Fasten eight Tridair fasteners.

The removed panel is shown in Fig. 2 (a) and the posture of the maintainer while removing the panel is shown in Fig. 2 (b). This task was assessed to have a RULA score of 5.

a b

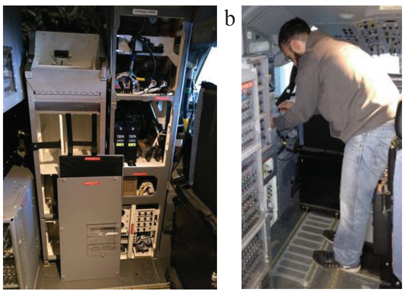

Fig. 2. Task 1: Upper Cover (a) Location (b) Posture of Operator

4.2 Task 2: Remove and Replace Lower Cover

Maintenance activities performed for the lower cover:
Task 2.1: Unfasten six Tridair fasteners
Task 2.2: Fasten six Tridair fasteners.

The removed panel is shown in Fig. 3 (a) and the posture of the maintainer while removing the panel is shown in Fig. 3 (b). This task was assessed to have a RULA score of 6. Note that only the unfastening and fastening times were recorded for this task.

a b

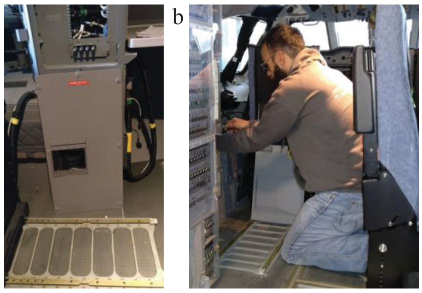

Fig. 3. Task 2: Lower Cover (a) Location (b) Posture of Operator

4.3 Task 3: Remove and Replace Two Avionics Boxes

Maintenance activities to be performed for the lower cover:
Task 3.1: Unfasten thumbscrew on avionics box 1
Task 3.2: Remove avionics box 1 and place on floor
Task 3.3: Unfasten thumbscrew on avionics box 2
Task 3.4: Remove avionics box 2 and place on floor
Task 3.5: Replace avionics box 2
Task 3.6: Fasten thumbscrew for avionics box 2
Task 3.7: Replace avionics box 1
Task 3.8: Fasten thumbscrew for avionics box 1.

The avionics boxes are shown in Fig. 4 (a) and the posture of the maintainer while removing the panel is shown in Fig. 4 (b). This task was assessed to have a RULA score of 5. The thumbscrew hold down fastener was modelled as a thumbscrew + butterfly clip for the MIL-STD-472 prediction.

a b

Fig. 4. Task 3: Avionics Boxes (a) Location (b) Posture of Operator

4.4 Task 4: Avionics Rack Cover

Maintenance activities performed for the avionics rack starboard cover:
Task 4.1: Unfasten nineteen captive Allen bolts
Task 4.2: Remove the cover and position it on the floor

Task 4.3: Pick up the cover and aligning it in position
Task 4.4: Fasten nineteen captive Allen bolts.

The avionics rack cover is shown in Fig. 5. It can also be seen in Fig. 5 that due to the shape and the size of the cover, the posture changes from top to bottom, and the arm is both above and below the shoulder. It is also necessary to support the panel during reassembly. This task was assessed to have a RULA score of 3. The captive Allen bolts were modelled as Tridair fasteners for the MIL-STD-472 prediction.

a b c

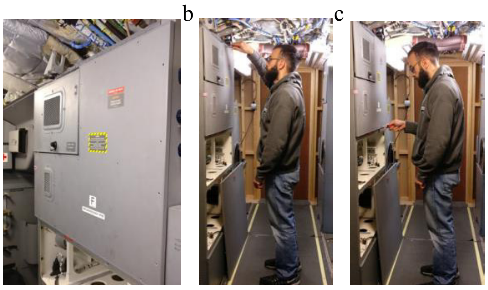

Fig. 5. Task 4: Avionics Rack Cover (a) Location (b) Posture of Operator for Upper Fasteners and (c) Lower Fasteners

5. Results

Each task was performed five times by a single student operator and the time recorded using hand timing for each sub-task. The operator's postures were then recreated using the Human Posture Analysis module in CATIA v5 as shown in Fig. 6 to obtain the postural scores. The maintenance task times were also predicted using the MIL-HDBK-472 Procedure V standard task times and the automated maintainability prediction tool.

Fig. 6. Postures for the 4 maintenance tasks

The results from the experimental trials, MIL-HDBK-472 standard task times and the automated maintainability prediction tool are shown in Figs 7 – 10.

A summary of the results is shown in Table 2 in which the time predictions from MIL-HDBK-472 and the automated prediction tool are compared with the average time for the experimental trials. A time prediction calculated using the Boothroyd, Dewhurst and Knight [16] Design for Manual Assembly method is also included for comparison. When applying the Boothroyd method, it was assumed that the disassembly time is equal to the assembly time.

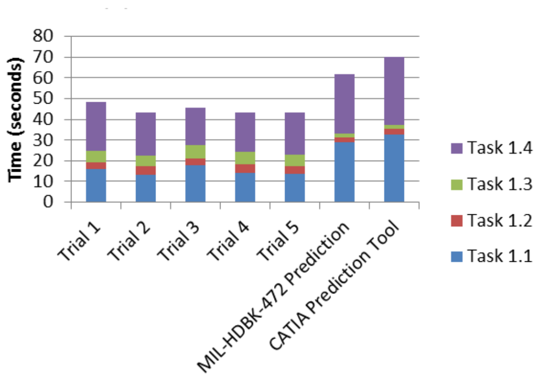

Fig. 7. Upper Cover Results

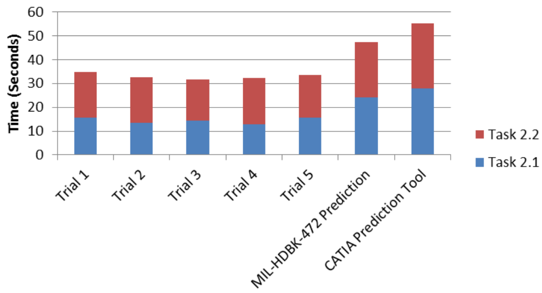

Fig. 8. Lower Cover Results

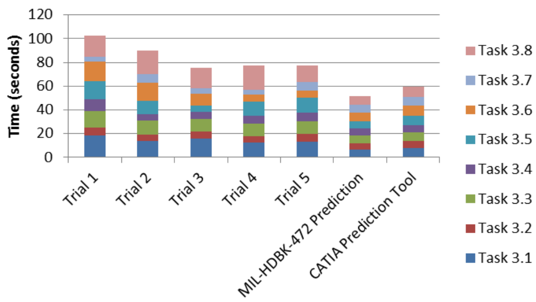

Fig. 9. Avionics Box Results

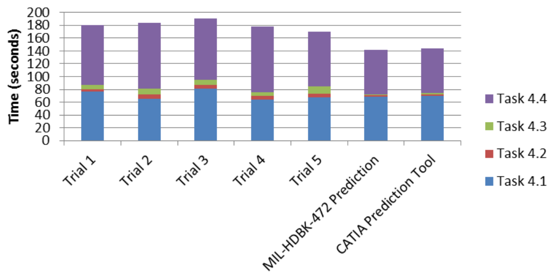

Fig. 10. Avionics Rack Cover Results

Table 2. Comparison of % Error between Trials and Predictions.

	Trials Average (s)	MIL-HDBK-472 (s)	%Error	Automated prediction tool (s)	%Error	Boothroyd and Dewhurst (s)	%Error
Upper Cover	45	62	38	70	57	40	12
Lower Cover	33	47	44	55	68	32	3
Avionics Boxes	85	52	39	60	29	66	22
Avionics Rack Cover	180	141	22	143	21	168	7
Average % Error			36		44		11

6. Discussion and Conclusions

The automated maintainability prediction tool has been created successfully and tested for a range of simple maintenance tasks. It is easy to use, and allows the maintenance task time for a product designed in CATIA to be rapidly assessed. However, it can be seen from the results summary in Table 2 that the error for the CATIA prediction tool is relatively high, varying from 21 to 68%. When comparing the elemental maintenance task times from MIL-HDBK-472 and the physical trials it is clear that the main source of the time difference is in the elemental task times. For example, the quoted disassembly time in MIL-HDBK-472 for a Tridair fastener is 3.6 s, whereas the average measured time from the upper cover trial was 1.9 s (min. 1.6 s, max. 2.2 s). The list of elemental maintenance actions in MIL-HDBK-472 is also relatively limited, with only eight fastener types, and no ability to adjust times based on the number of turns required to remove or replace the fastener. Hence, in many cases the designer must select the most similar fastener in the database which may not represent the actual fastener in the design. The average experimental elemental task times are summarised in Table 3, with the corresponding elemental task time from MIL-HDBK-472 where available.

Table 3. Average Elemental Task Times from Experiments.

	Unfasten (s) Experimental	Fasten (s) Experimental	Unfasten (s) MIL-HDBK-472	Fasten (s) MIL-HDBK-472
Tridair Fastener	1.9	2.5	3.6	3.6
Thumbscrew Hold-down	13.1	14.4	N/A	N/A
Captive Allen Bolt	3.7	5.1	N/A	N/A

The results from the Boothroyd and Dewhurst Design for Assembly method are substantially closer to the experimental results, with the percentage error ranging from 3 to 22 %. This is due to the more complex Boothroyd and Dewhurst method which includes time factors for handling, insertion and fastening as well as allowances for accessibility, visibility and part weight, rather than a single time value per fastener. However, the Boothroyd and Dewhurst method is more time consuming to apply and requires more knowledge from the designer. Despite the limited accuracy of the results, the tool still provides a useful way for designers to assess the maintainability of their designs. In particular, it can be used to rapidly compare the maintainability of different design alternatives at an early stage in the design process and helps to engage designers with the maintainability assessment process. It is recommended that a larger set of experimental trials should be undertaken to provide a more realistic set of elemental maintenance action times, covering a wider range of tasks to further improve the maintainability tool.

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References

[1] Friend, CH. Aircraft Maintenance Management. UK: Longman Group; 1992.

[2] MIL-HDBBK-470A. Designing and developing maintainable products and systems, Department of Defense. Philadelphia: Navy Publishing and Printing Office; 1997.

[3] DOD-HDBK-791. Maintainability Design Techniques, Department of Defense. Philadelphia: Navy Publishing and Printing Office; 1988.

[4] MIL-HDBK-472 Notice 1. Maintainability prediction, Department of Defense. Philadelphia: Navy Publishing and Printing Office;1984.

[5] McAtamney LE and Corlett N. RULA: A survey method for the investigation of work-related upper limb disorders, *Applied Ergonomics* 1993; 24:91-99.

[6] Karhu O, Kansi P and Kuorinka I. Correcting working postures in industry: A practical method for analysis. *Applied Ergonomics* 1977; 8:199-201.

[7] Calder IC. and Potvin JR., A polynomial equation to predict low back compression force: accounting for the effects of load height on instability, *Work* 2012; 41:388-393

[8] DOD-HDBK-791. Maintainability Design Technique, Military Handbook. Washington: Department of Defense; 1988.

[9] Meister D. The History of Human Factors and Ergonomics. Mahwah, N.J.: Lawrence Erlbaum Associates; 1999.

[10] Hignett S and McAtamney L, Rapid Entire Body Assessment (REBA) *Applied Ergonomics* 2000; 31:201–205.

[11] Waters TR, Putz-Anderson V and Garg A. Applications manual for the Revised NIOSH Lifting Equation. Cincinnati, Ohio:US Department of Health and Human Services, 1994.

[12] Di Gironimo G, Monacellia G and Patalano S. Design Methodology for Maintainabiity of Automotive Components in Virtual Environment. International Design Conference – Design 2004, Dubrovnik, May 18 – 21.

[13]Colombini D, Occhipinti E, Cairoli S, Baracco A. Proposta e validazione preliminare di una check-list per la stima dell'esposizione lavorativa a movimenti e sforzi ripetuti degli arti superiori, *Med. Lav*. 2000;91:470-485.

[14] Zhao X. Design for Maintainability Integrated with CAD. MSc thesis, Cranfield University, 2015.

[15] Arvanitopoulos-Darginis K. Design for Maintainability Integrated with CAD – An experimental Case Study/ MSc thesis, Cranfield University, 2016.

[16] Boothroyd G, Dewhurst G and Knight WA. Design for Manufacture and Assembly, Third Edition, UK: CRC Press